NASA HERMeS Hall Thruster Electrical Configuration Characterization

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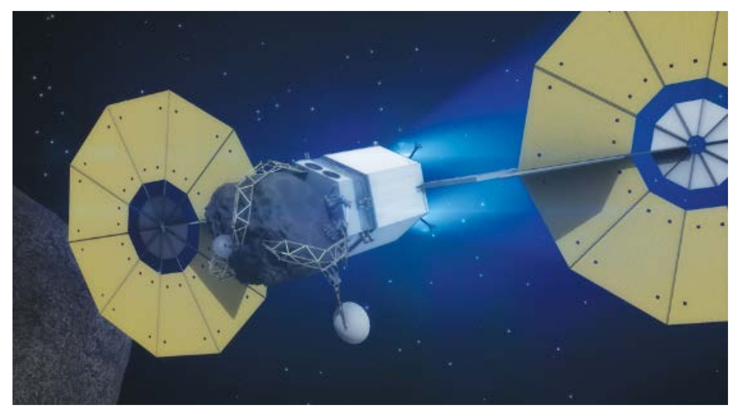
Motivation

- As higher-powered Hall thrusters have become more widely planed in future NASA missions there are consideration that need to be studied and understood to realize a low-risk path forward.
  - One such consideration is to ensure that the development propulsion system is tested in as close as a space environment as possible.
  - When direct simulation of a in-space environment is not possible it is important to develop a understanding and know-how to confidently project in-space operation from ground based operation.

How do we get from Lab to Flight?



Motivation

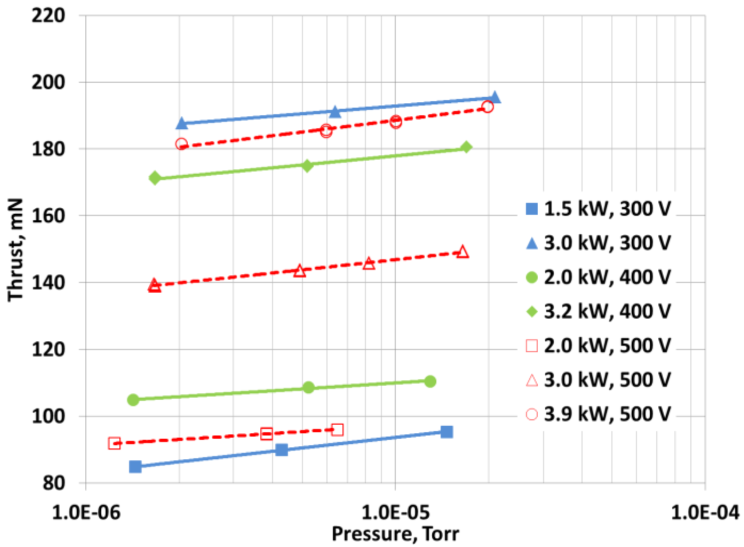
- Potential facility interaction considerations that need to be studied and understood.

  - Propellant Ingestion:
    - One of the long understood facility interaction concerns with Hall thruster devices is the potential of propellant ingestion from the elevated background pressure of a ground-based vacuum chamber as compared to in-space pressures.

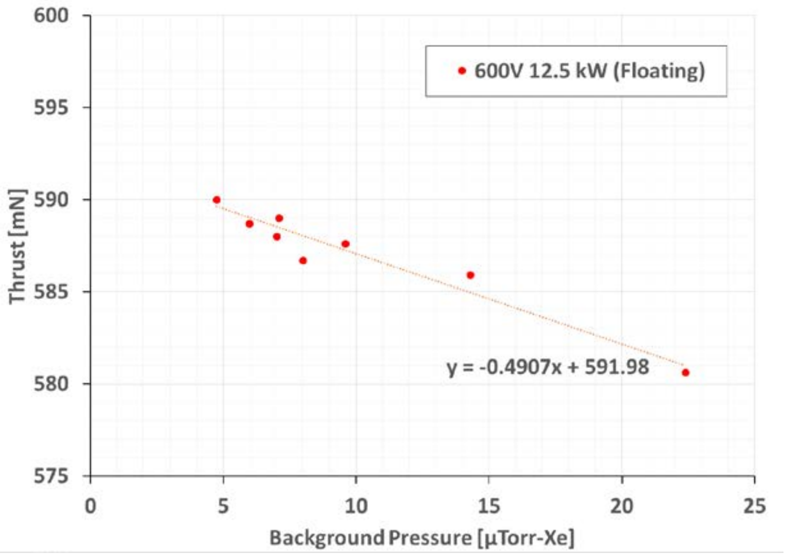
  - Electrical Interaction:
    - A relatively new Hall thruster facility interaction concern, identified and discussed in the Hall thruster community, pertains to the electrical interaction of a conducting vacuum facility with the plasma processes of a Hall thruster main plasma discharge, cathode coupling, and the thruster plasma plume.

The primary goal of this presentation, and associated paper, is to investigate any potential concerns of facility-thruster electrical interaction and to quantify the influence of such interaction on the TDU-1 Hall thruster.

Previous Facility Interaction Investigations



<u>Figure</u>. HiVHAC thrust variation as a function of facility background pressure (xenon) during the pressure sensitivity test in NASA GRC's VF-5.



<u>Figure</u>. HERMeS TDU-1 performance as a function of background pressure for the 600V 12.5kW throttle condition.

- <u>Propellant Ingestion</u>:
  - Past Hall thruster studies have indicated that some thruster configuration are susceptible to background pressure.
  - Performance as a function of background pressure has a opposite trend with the HERMeS Hall thruster design.
  - Further details can be found in AIAA-2016-4828 "*Facility Effect Characterization Test of NASA's HERMeS Hall Thruster*"

Electrical Configuration

- The electrical configuration of a Hall thruster, in relation to a conducting vacuum facility, has been recently identified as a concern that needs to be considered in the development and qualification of new Hall thruster propulsion systems.

- The electrical configuration of a Hall thruster in a conducting ground based vacuum facility can be described in two primary configurations with a newly envisioned third option.
    1. Thruster body is electrically tied to the facility ground.
    2. Thruster body is isolated from the facility ground and allowed to float with respect to the local plasma potential.
    3. Thruster body isolated from the vacuum facility chamber ground and electrically tied to the floating cathode common.

Electrical Configuration (*Grounded*)

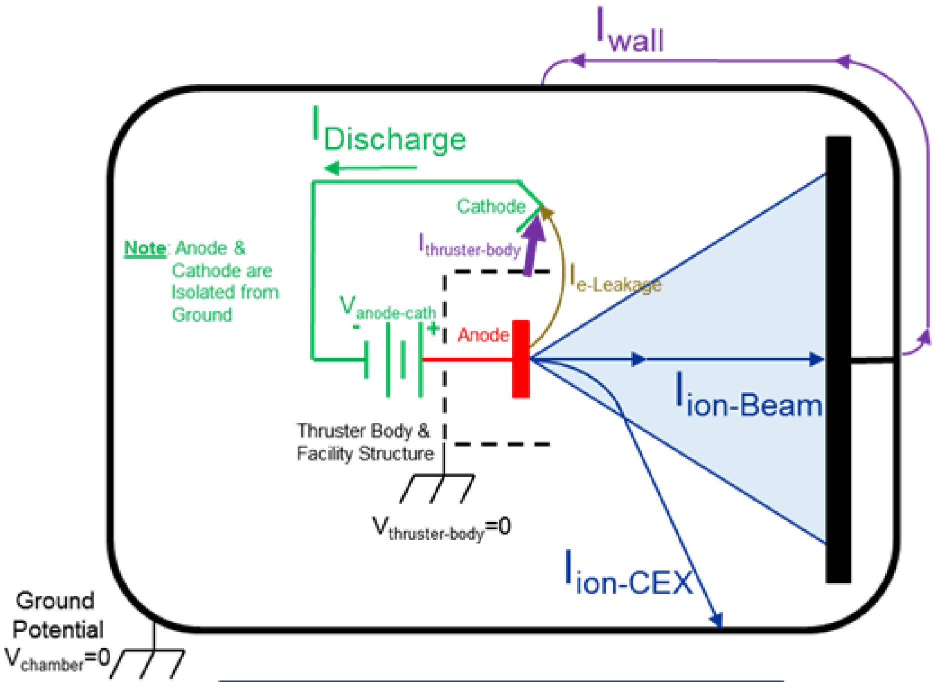


Figure. Illustration of a Hall thruster body grounded electrical configurations for ground based Hall thruster testing.

A majority of Hall thruster development and qualification testing has been conducted in this electrical configuration over the past few decades.

- Grounded Thruster Body
  (electrically connected to conducting vacuum facility chamber)
  - Electrons can travel with the ion beam,
  - Electrons can also find alternate low-resistance paths through the electrically conducting material:
    - Thruster body
    - Diagnostic equipment
    - Structure
  - Any electrons traveling through the lower resistance path of the chamber walls meet up with the ions in the beam, and/or Charge-Exchange (CEX) ions, on the walls of the chamber and/or grounded beam dump.

Electrical Configuration (*Floating*)

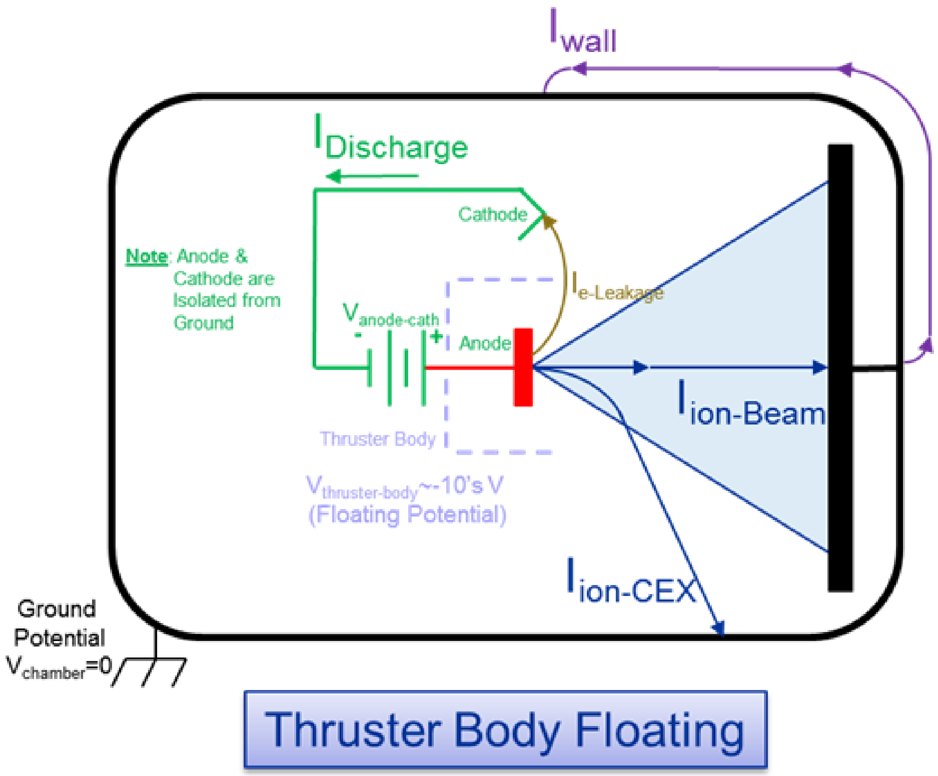


Figure. **Illustration of a Hall thruster body floating electrical configurations for ground based Hall thruster testing.**

- Floating Thruster Body
  (electrically isolated from conducting vacuum facility chamber)
  - The body of the thruster will float to a negative potential that balances out the ion and electron current collected by the thruster.
  - The electrons travel with the ion beam.
  - There are still potential for wall currents to occur in a conducting facility due to CEX ions and beam divergence.

Electrical Configuration (*Floating*)

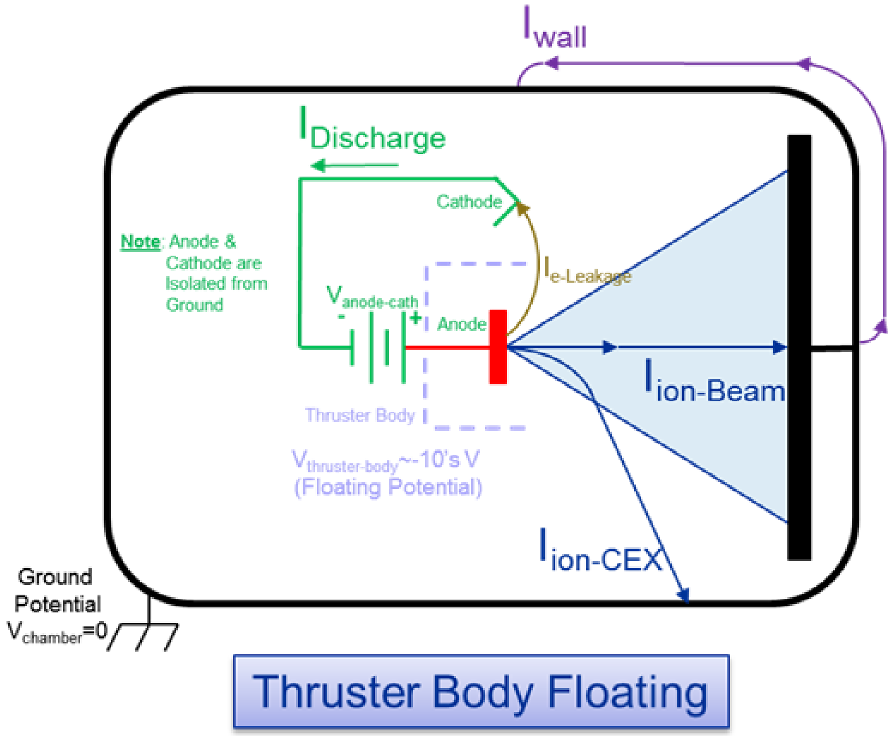


Figure. Illustration of a Hall thruster body floating electrical configurations for ground based Hall thruster testing.

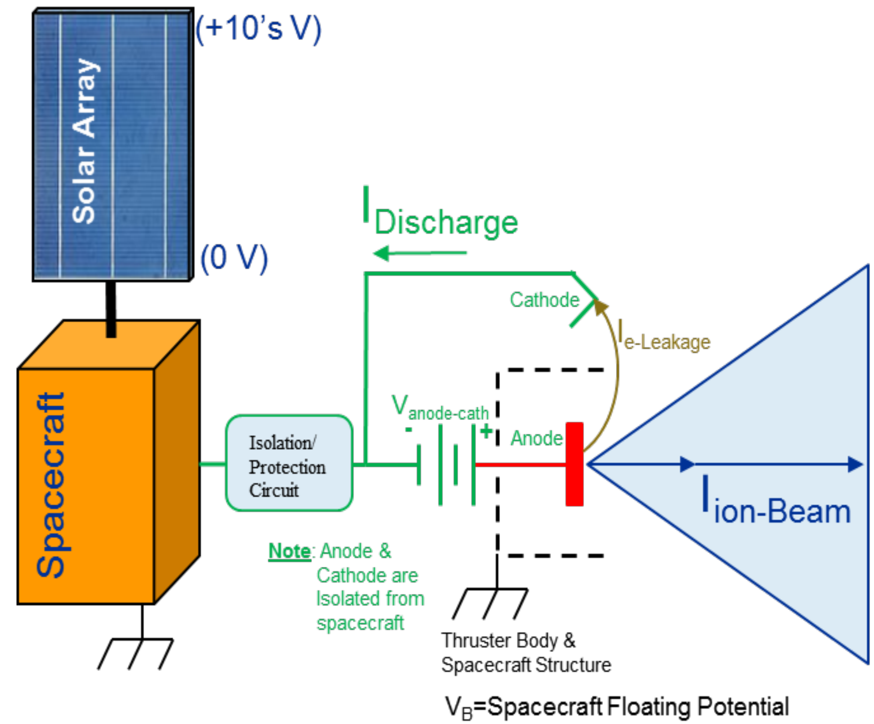


Figure. Illustration of a typical Hall thruster propulsion system electrical configuration on a spacecraft.

It is postulated that floating a Hall thruster body in a conducting vacuum chamber can provide a methodology for ground based testing to partially simulate the electrical environment that a Hall thruster will be subjected to in space by forcing the electrons to travel with the beam ions instead of taken a lower resistance path through the conducting vacuum chamber

Electrical Configuration (*Cathode-Tied*)

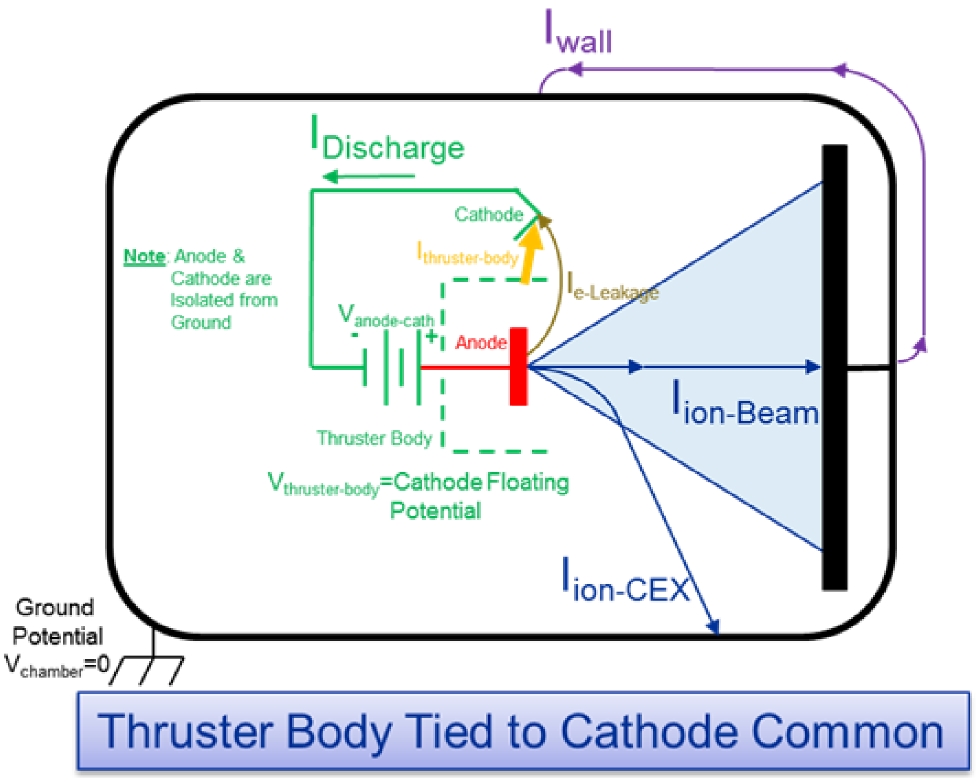
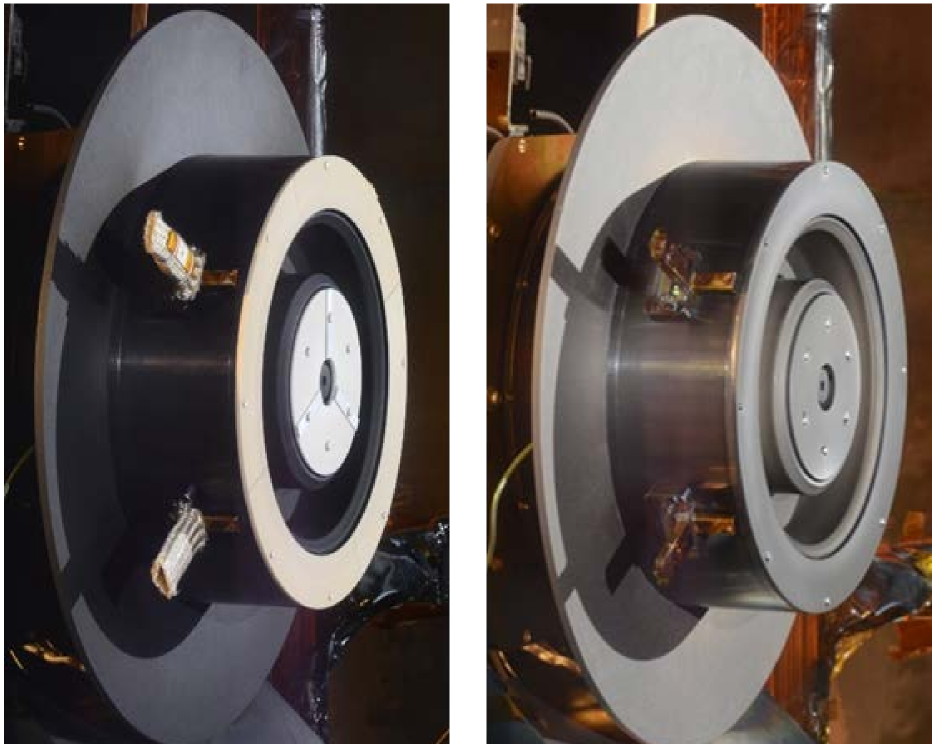


Figure. Illustration of a Hall thruster body tied to cathode common electrical configurations for ground based Hall thruster testing.

A similar electrical configuration employed by TAL Hall thrusters

- Thruster Body Tied to Cathode
  (Thruster body electrically connected to the cathode common and electrically isolated from the vacuum facility)
  - Electrons will travel with the ion beam to maintain charge neutrality.
  - Additional electrons are collected by the thruster body, similar to the grounded electrical configuration, but instead of finding a low resistance path through conducting facility and neutralizing the plume ions at the facility interfaces the electrons are forced to be emitted by the cathode and are not part of the charge balance in the plume.
  - There are still potential for wall currents to occur in a conducting facility due to CEX ions and beam divergence.

TDU-1 Hall Thruster (*Boundary Conditions*)



Dielectric (Al2O3)

Conducting (Graphite)

Figure. The HERMeS TDU-1 Hall thruster with dielectric (left) and conducting (right) boundary conditions on the exit plane plasma wetted surfaces.

- For the electrical configuration testing the TDU-1 thruster was configured with two different Boundary Conditions (BC).
  - Conducting (graphite pole covers)
  - Dielectric (Al_2O_3 pole covers)
- The thruster BC for this paper is defined as the exit plane plasma wetted surfaces that can interact with the electrons and ions generated by the plasma discharge.

Note: Only the exit plane poles were covered with a dielectric or conductor and the sides of the thruster and the radiator were left unchanged.

Facilities & Experimental Apparatus

- GRC Vacuum Facility 5
  - Pressure achieved by facility during thruster operation at 600V 12.5kW: 4.4 µTorr-Xe
- Thrust stand is of inverted pendulum design
- Plasma probes mounted in a package on radial-polar stages
  - Polar angle of 0° is the direction of the firing axis
  - Faraday probe (FP) swept continuously over ±110° at several distances axial positions from the thruster exit plane.
  - Retarding potential analyzer (RPA) data corrected with Langmuir probe (LP) data several radial positions
  - **E**x**B** (*Wien filter spectrometer*) data was acquired at 0°
- Ion gauge
  - Three EP configured ion gauges calibrated on xenon and reading Torr-Xe
  - One standard configured ion gauge (w/ an additional plasma screen) calibrated on air and reading Torr-air

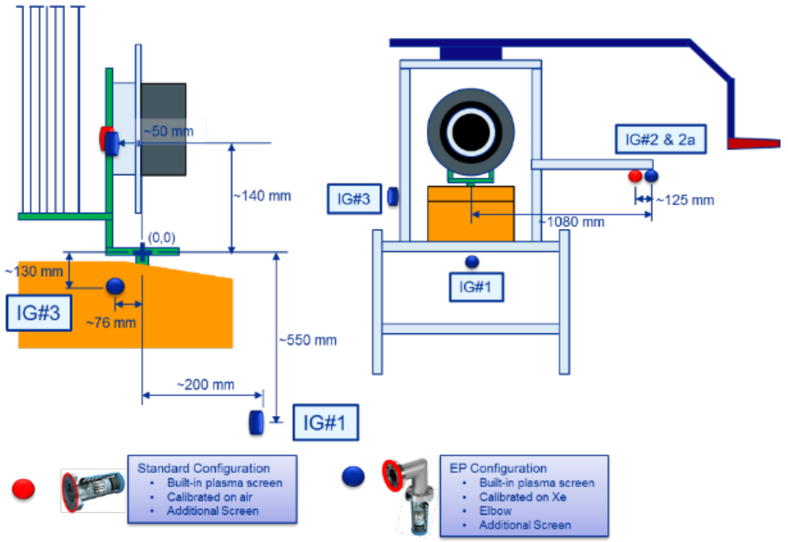


Figure Schematic of the internal ion gauge setup for the TDU-1 test campaign (not to scale).

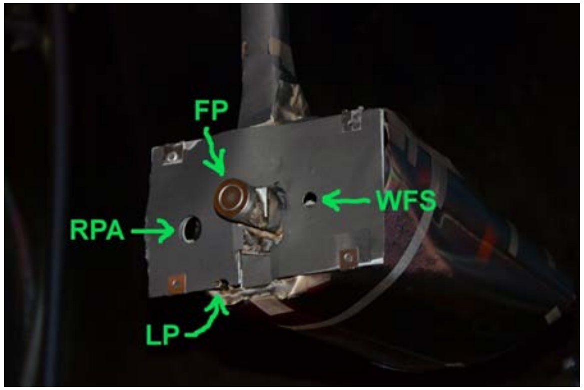
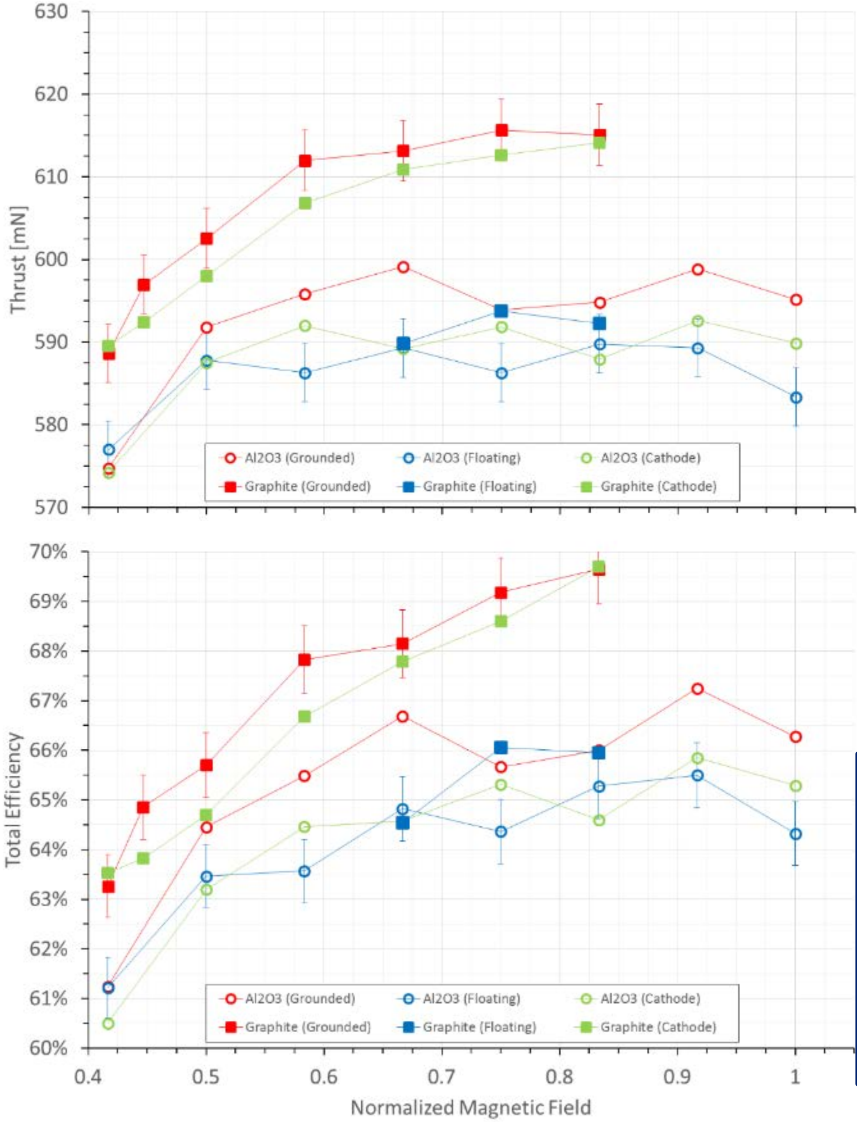


Figure 10. The plasma plume diagnostic system used for the TDU-1 test campaign.

RESULT & DISCUSSION

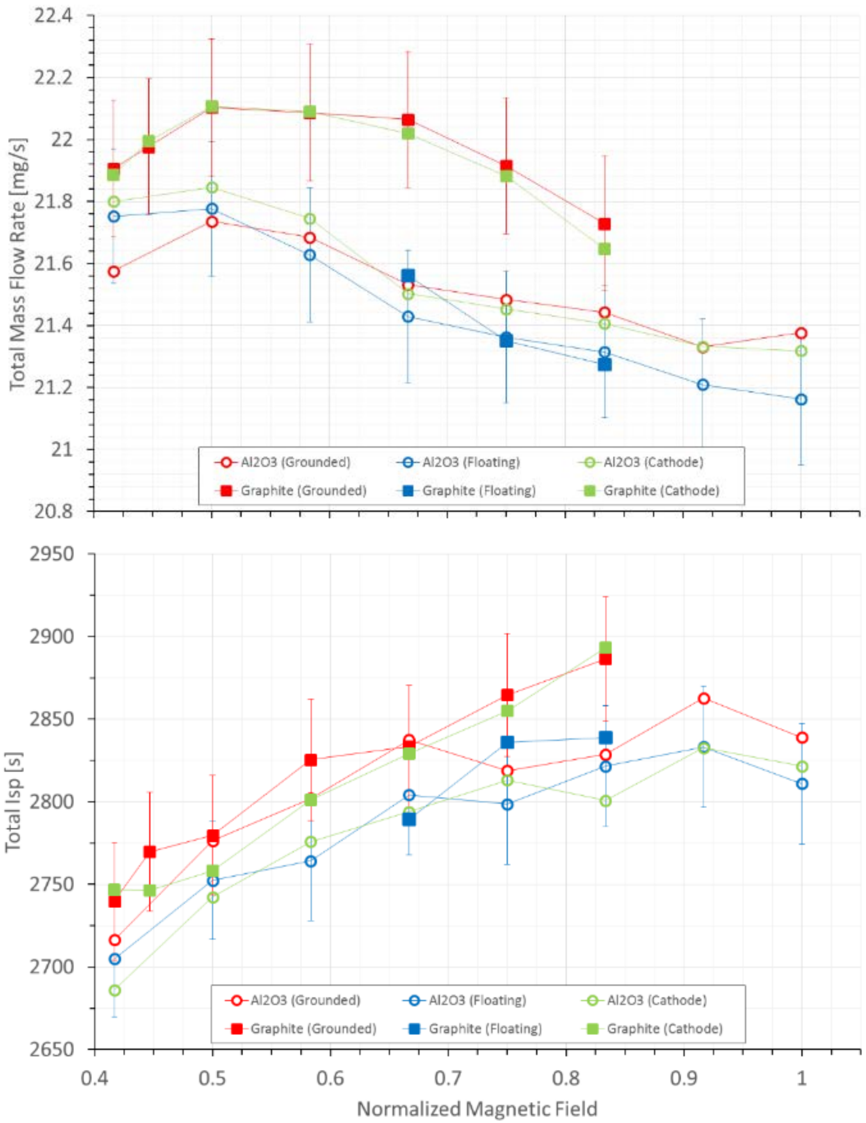
Thruster Performance



- The most significant finding was the performance decrease from the grounded to floating electrical configurations for both thruster BC.
  - Up to a **4% decrease** for the conductor from grounded to floating
  - The performance also decreased for the dielectric, but to a lesser extent
- Floating the conducting boundary condition resulted in the thruster performance falling with in the range of the dielectric

It is important to note that eclectically connecting the thruster body to the cathode common allows the performance to approach that of the grounded configuration while preventing beam electrons from finding alternative paths that are not present in space.

Thruster Performance



- Total mass flow rate required to meet the desired power level also indicates a measurable difference between grounded and floating configurations.
  - Floating configuration for the conducting BC needed approximately the same amount of xenon to reach 12.5kW
  - The spread in the dielectric BC over the electrical configuration is not large and falls into the uncertainty of the mass flow rate measurements
- The total Isp variation is not as large as the observed thrust and mass flow rates.

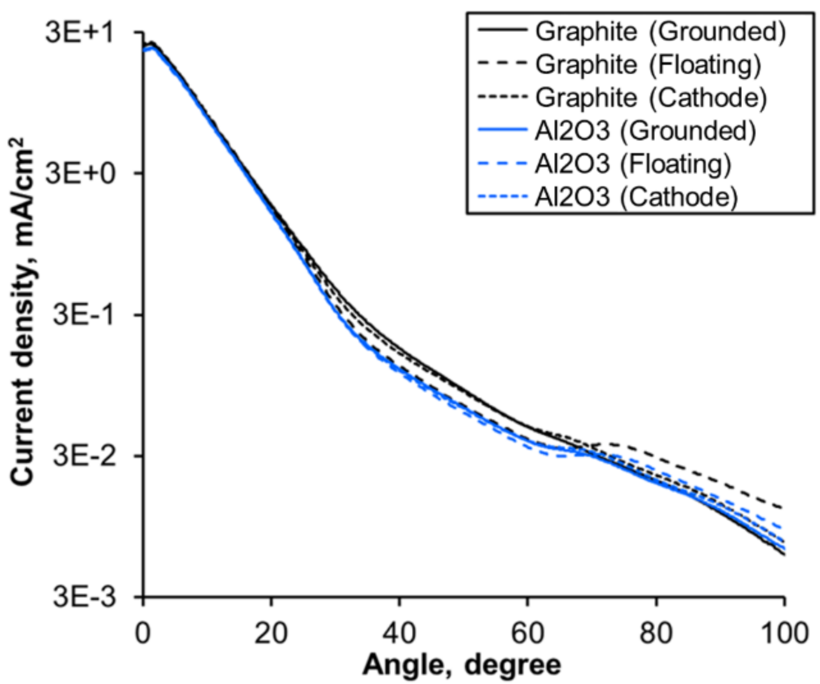
Thruster Performance

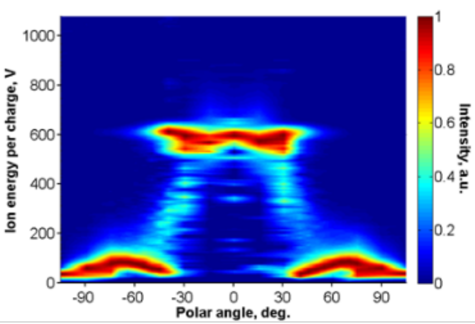
	Thruster Config.	Electrical Config.	Thrust [mN]	Total Efficiency	Total Mass Flow Rate [mg/s]	Id _RMS [A]	Id_Pk2Pk [A]	Thruster Body Current [A]	Thruster Body Voltage [V]	Thruster Body Voltage RMS [V]	Thruster Body Voltage Pk2Pk [V]
600V 12.5kW	Graphite	G	613	68.2%	22.06	3.98	18.6	2.73	0	-3	-22
		F	590	64.5%	21.56	3.38	13.2	0	-45	-53	-126
		Cath	611	67.8%	22.02	3.98	15.8	1.83	-9	-12	-36
	Al2O3	G	599	66.7%	21.53	3.48	12.2	1.36	0	-2	-14
		F	589	64.8%	21.43	3.19	12	0	-31	-38	-78
		Cath	589	64.6%	21.50	3.42	11.8	0.81	-10	-11	-30

- A thruster body current of **2.72 A** was measured in the conducting BC in the grounded configuration
  - 13% of the total discharge current
- Floating the thruster with a conducting
  - -45 V steady state floating voltage with respect to the chamber ground
  - -126 V time-resolved Pk2Pk
- The dielectric BC had similar trends(~50% decease) compared to the conducting BC

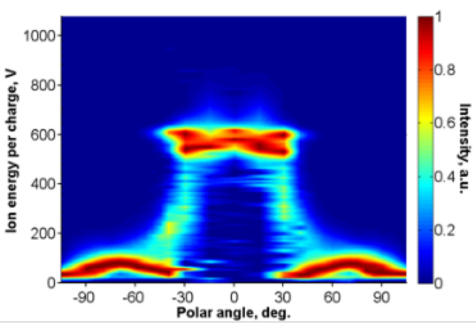
The cathode electrical configuration provided improvements over the floating configuration

Plume Characterization





Graphite (Grounded)



Al2O3 (Grounded)

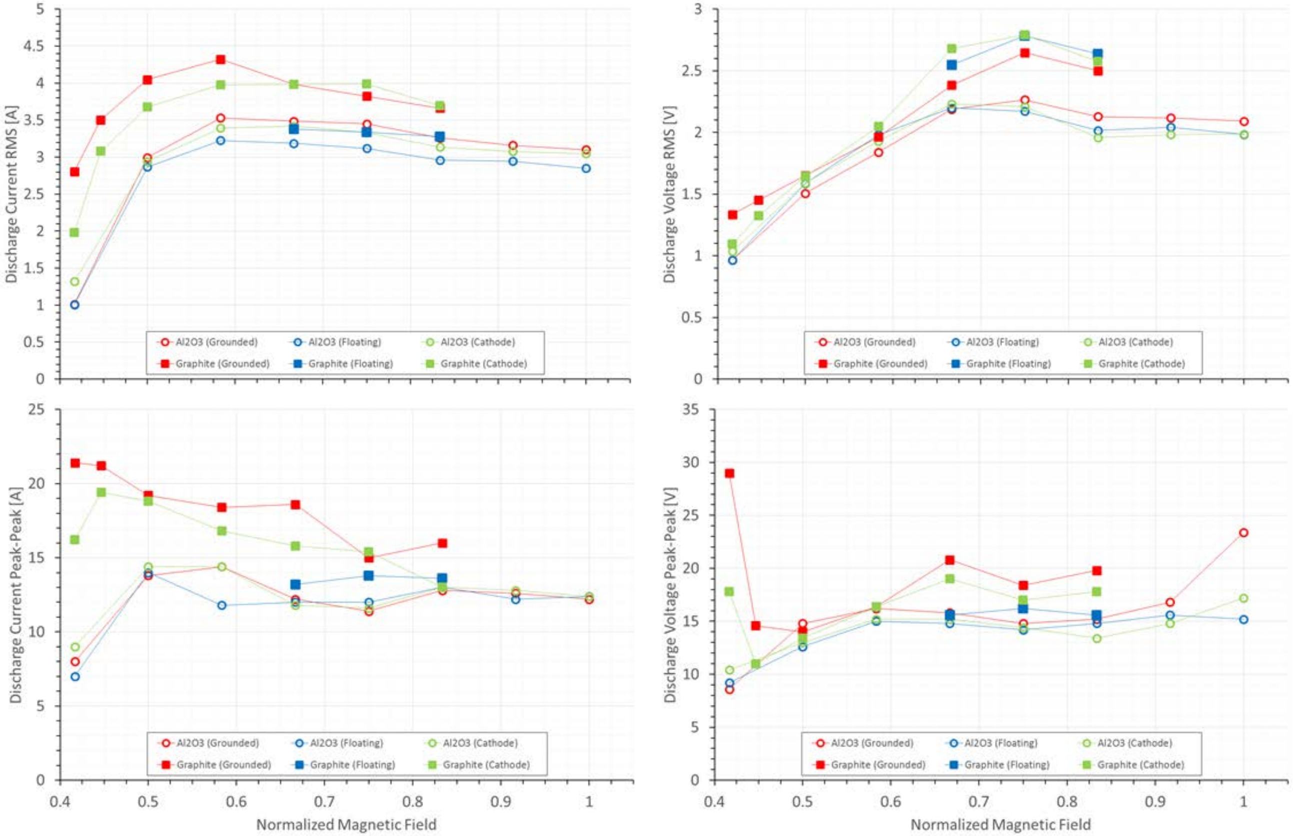
- The TDU-1 thruster was subjected to a series of plasma plume diagnostics observed over the six configurations tested.
- The conducting BC in the grounded and cathode electrical configuration had a slightly different plume profile compared to the dielectric BC, and three electrical configurations, and the floating conducting BC.
  - Floating the thruster is similar to the dielectric BC
- The primary ion most probable energy profile over the width of the ion beam was obtained by the RPA.
  - Changing the electrical configurations and the BC have measurable differences in the primary ion cone.

Plume Characterization

	Thruster Config.	Electrical Config.	Plume Momentum-Weighted Divergence Angle	Plume High Energy Ion Cone	Charged Species Fractions		
					Xe+	Xe++	Xe+++
600V 12.5kW	Graphite	G	19.3°	75-90°	84.0%	12.1%	3.9%
		F	19.2°	60-65°	86.9%	9.7%	3.4%
		Cath	19.3°	70-75°	86.1%	10.1%	3.8%
	Al2O3	G	19.5°	60-65°	87.9%	8.6%	3.6%
		F	19.8°	55-60°	87.0%	9.3%	3.7%
		Cath	19.6°	60-65°	87.1%	9.1%	3.8%

- Plume momentum-weighted divergence angle indicated minimal changes between electric configurations for a given BC
- The conducting BC had a larger primary ion cone than the dielectric BC, except for the floating configurations.
  - Up to 66% decrease from conducting to dielectric BC.
  - The conducting BC in the floating configuration primary ion cone was approximately the same as the all three electrical configuration with the dielectric BC.
- ExB probe results indicates conducting BC has a lower fraction of singly-charge ions and greater double-charge ions than the dielectric BC.

Stability Characterization

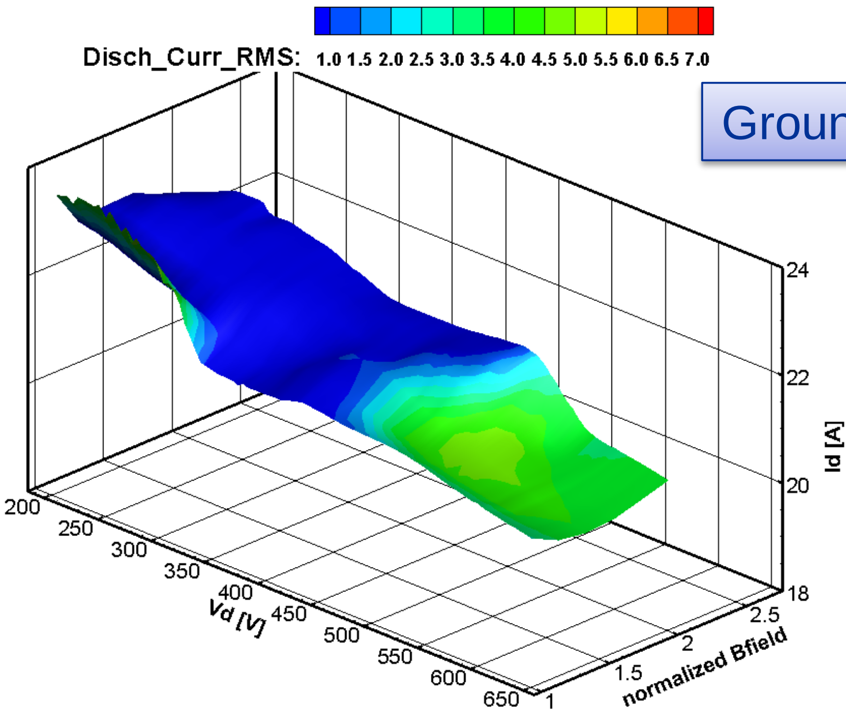


- The thruster stability is another parameter that can influence the performance.
- The discharge current higher RMS and Pk2Pk for the conducting BC compared to the dielectric BC
  - Except for the floating configuration
- The discharge voltage RMS and Pk2Pk values showed an interesting trend with applied magnetic field.

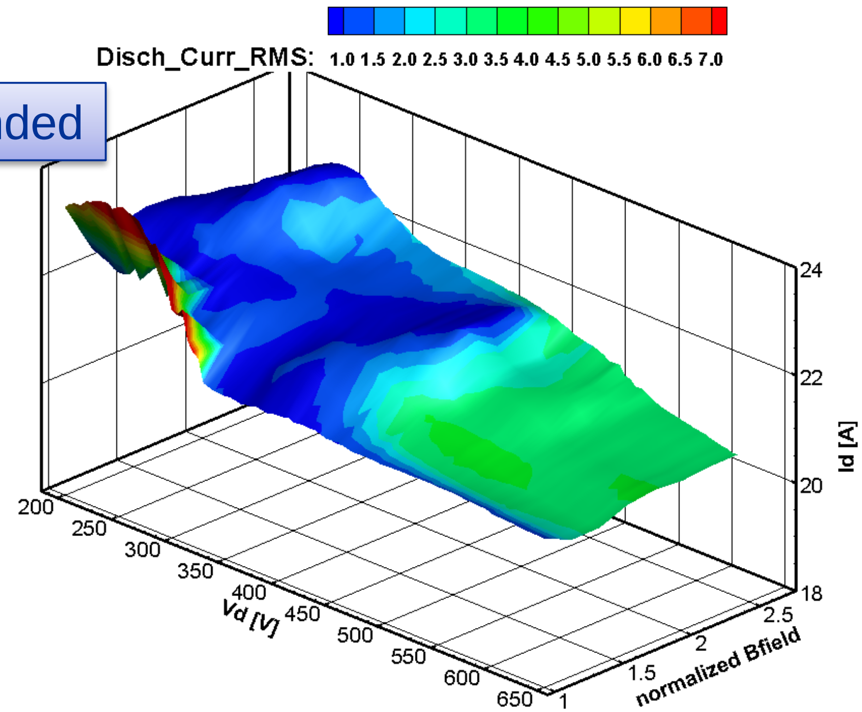
Stability Characterization

(Boundary Conditions)

Grounded



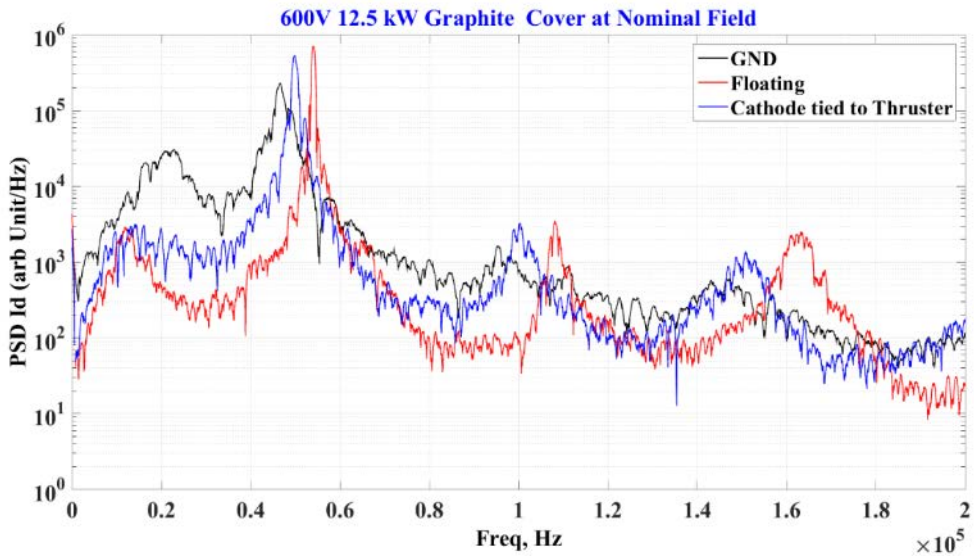
Graphite

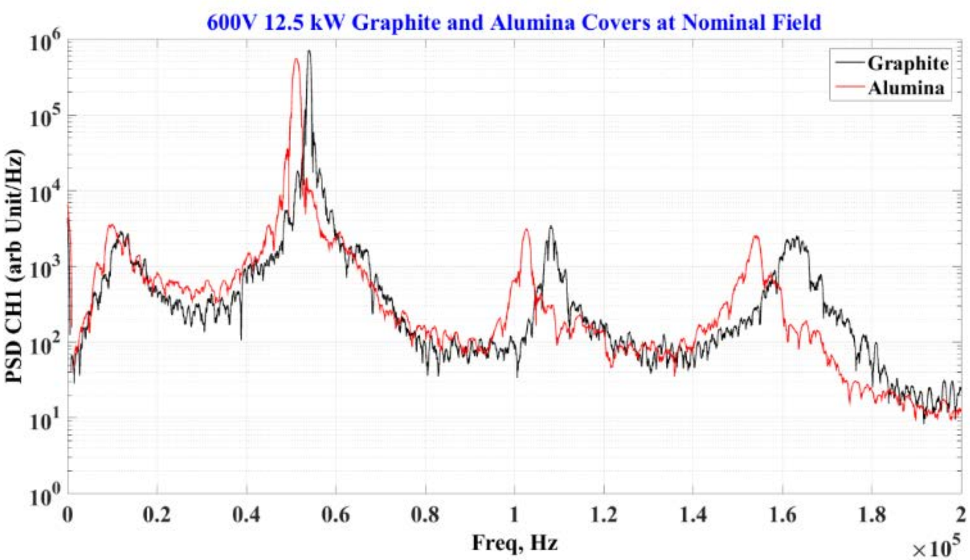


Al2O3

- The IVB maps of the six configuration tested and the trends with pressure can provide valuable information on how a thruster will preform from ground based to in space operation.
- *Further details can be found in AIAA-2016-4828 "Performance, Facility Pressure Effects, and Stability Characterization Tests of NASA's 12.5-kW Hall Effect Rocket with Magnetic Shielding Thruster"*

Stability Characterization
(PSD)





- Comparisons of electrical configuration for the conducting BC
  - Noticeable shift in the both the peak positions and amplitudes
  - Primary peak shifts have been associated with ionization and acceleration locations and characteristic lengths
    - Low frequency can represent a longer ionization and acceleration region
    - More ionization can occur in the discharge channel leading to a slightly less divergence and primary ion distribution

Conclusions

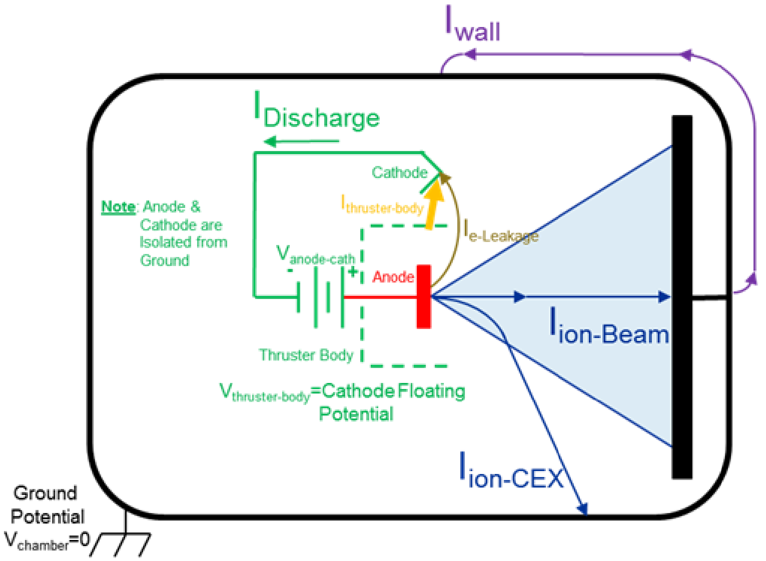
- The performance of the TDU-1 decreased by 2% to 4% in thrust between the grounded and floating electrical configurations.
  - Performance almost completely returns to the grounded results in the thruster body electrical connect to the cathode common.

- Grounded thruster body telemetry indicated a large electron current, approximately 10% of the discharge current, from the thruster body to the facility ground in this configuration.
  - This configuration cannot be replicated in space and might result in the Hall thruster operating differently in flight.

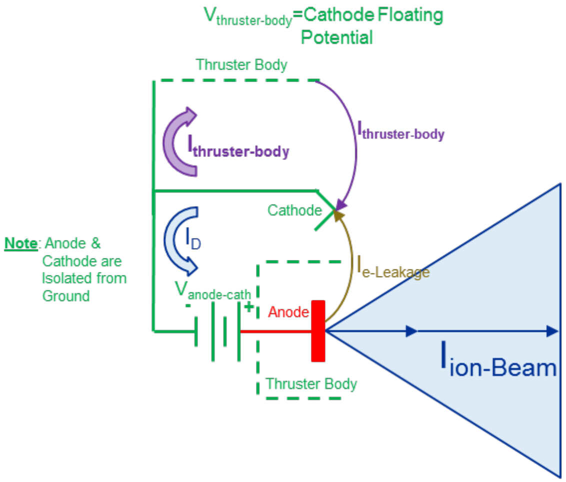
- The high-energy primary ion cone was 5° - 20° narrower for the dielectric boundary condition compared to the conducting boundary condition.

- The results for the dielectric thruster boundary condition, while not as definitive with the conducting configuration, still has noticeable benefits.
  - *The results presented here are only a part of the overall trade and while important may be out weighed by other processes (i.e. wear of thruster surfaces)*

Conclusions



Thruster Body Tied to Cathode Common



$$I_{Discharge} = I_{ion-Beam} + I_{e-Leakage}$$

$$I_{Cathode} = I_{ion-Beam} + I_{e-Leakage} + I_{Thruster-Body}$$

Thruster Body Tied to Cathode Common

- **At this stage of development of the HERMeS propulsion system, the thruster body electrically connected to the cathode common and isolated from the spacecraft chassis is a feasible option for future spacecraft architecture.**
  - *A primary benefit is the knowledge of the electrons collected by the thruster body will be directed through the cathode and not allowed to find a low resistance path through the chamber, which will be absent during in-space operation.*

NASA